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Methane emissions in China 2007

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ABSTRACT

In contrast to the ever-increasing focus on China's CO_2 emissions, little attention has been given to its CH_4 emissions, the second largest greenhouse gas. Presented in this paper is a comprehensive assessment of the CH_4 emissions in Mainland China by source and region based on the latest statistical data and research literatures available. The total CH_4 emission in China 2007 is estimated as 38.6 Tg, one and a half times of that in USA. Even by the lower IPCC global warming potential (GWP) factor of 25, it corresponds to 964.1 Mt CO_2-eq, in magnitude up to one seventh of China's CO_2 emission and greater than the nationwide gross CO_2 emissions in Australia, Canada, and Germany in 2007. As the leading emission source, energy activities are responsible for 45.3% of the total emission, agricultural activities contribute a comparable share of 40.9%, followed by waste management of 13.8%. Among all the 11 major emission sources, coal mining (38.3% of the total), enteric fermentation (21.4%) and rice cultivation (14.4%) essentially shape the CH_4 emission profile for China, quite different from that for USA which is characterized by prominent emissions from enteric fermentation, municipal solid waste landfill and natural gas leakage. The Western and Central areas contribute 70.9% of the total nationwide emission and Shanxi is the largest regional CH_4 emitter with an amount of 4.6 Tg. The five regions of Xizang (Tibet), Shanxi, Qinghai, Ningxia, and Guizhou are identified with the largest emissions per-capita and emission intensities. In contrast to the focused areas of CO_2 emission reduction mainly in the energy-intensive eastern regions, the mitigation potential of CH_4 emissions in the western and central regions is huge by integrating emission quantity and structure with emission per-capita and emission intensity at the regional level. Corresponding policy-making implications for CH_4 emission mitigation in China are addressed.

Contents

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1. Introduction

Regarding the global climate change [1], most countries have committed to set their greenhouse gas (GHG) emission targets [2–4]. Effective mitigation necessitates a clear understanding of the current emission status and situation. As China has been considered as the largest CO_2 emitter in the world since 2007 [5], many studies have contributed to the CO_2 emission estimation and related assessment for the mitigation potential in China (e.g., [6–15]). Meanwhile, the Chinese government has committed to reduce 40–45% CO_2 emissions per unit of the Gross Domestic Product (GDP) by 2020 relative to the level of 2005 [16] and assigned a CO_2 emission intensity reduction goal of 17% between 2011 and 2015 in the 12th Five-Year Plan (2011–2015) [17].

Methane (CH_4) is another potent greenhouse gas, having a global warming potential (GWP) 72 or 25 times greater than that of carbon dioxide over a horizon of 20 or 100 years, respectively, by the IPCC fourth assessment report [18]. As illustrated by the IPCC global inventory for 2004, methane emissions by the lower GWP factor of 21 (over the 100 year horizon in the IPCC third assessment report) accounted for 14.3% of the global anthropogenic GHG emissions [18]. Methane emissions in China are also remarkably significant. According to the first official GHG emission inventory of China for the year of 1994 from the Initial National Communication on Climate Change of China, methane by the lower GWP factor of 21 contributed 19.4% of the total national-wide GHG emission in terms of CO_2, CH_4 and N_2O in 1994 [19]. Chen and Zhang [13] reported that methane by the GWP factor of 21 accounted for 11.2% of the total GHG emission by 26 industrial sectors of the Chinese economy in 2007 covering three of the most concerned types (CO_2, CH_4 and N_2O). Recently, the latest official GHG emission inventory of China from the Second National Communication on Climate Change of China [20] reported that methane by the GWP factor of 21 contributed 12.5% to the total national GHG emission covering six GHGs covered by UNFCCC in 2005. In contrast to the ever-increasing focus on China's CO_2 emissions, however, the important role played by methane in the GHG emission inventory for China and even for the world has not received the attention it deserves so far.

Extensive studies have been made to estimate anthropogenic CH_4 emissions in China from notable sources, such as rice cultivation (e.g., [21–33]), enteric fermentation and manure management (e.g., [34–39]), agricultural activities (e.g., [40–44]), coal mining (e.g., [45–50]), fuel combustion (e.g., [51–54]), municipal solid waste (MSW) treatment (e.g., [55–60]) and wastewater management (e.g., [61–63]). To evaluate the whole CH_4 emission inventory of China, some concrete efforts have been made to cover some emission sources in early years such as 1980s [64], 1990 [65], 1994 [19,66], 2000 [67,68] and some recent years such as 2005 [20,68,69] and 2007 [70]. In particular, the direct and indirect methane emissions of single or multi-scale socio-economies in China have been widely explored by Chen and his collaborators in their series of works for multi-scale systems input–output analysis of environmental emissions [71–74]. Although there is clearly a growing concern about anthropogenic CH_4 emissions from the notable sources at different scales in China, a rather systematic study covering all the major emission sources at a national scale for recent years remains yet to be performed.

Because of the centralized hierarchy of administration in China, the national GHG emission mitigation objective has been promptly transformed into regional emission mitigation targets [17,75]. As the mode of considering GHG reduction along with economic growth target has become an inevitable choice [16,17], the simple measurement for CO_2 emission mitigation without the consideration of other GHGs such as CH_4 may not be adequate. It is therefore necessary to provide detailed countermeasures for CH_4 emission mitigation at both the national and regional levels. However, most studies have focused at the characteristics of regional CO_2 emissions in China, and the corresponding schemes of reduction allocation among regions [76–81]. Few researchers have used province-level data to address the CH_4 emissions by region and analyzed regional differences in CH_4 emissions, though regional inventory is the prerequisite for national inventory.

Presented in this paper is a detailed bottom-up estimation of CH_4 emissions from anthropogenic sources in China 2007 based on the latest available statistics and research literatures, covering the major sources including enteric fermentation, manure management, rice cultivation, coal mining, oil and natural gas system leakage, bio-fuel combustion, waste management, etc. As done to the whole emission inventory, methane emissions at the regional level are evaluated in detail in terms of emission component, emission per-capita, and emission intensity, in order to assess the regional emission performance. Furthermore, a systematic assessment by source and region is presented for the purpose of emission mitigation.

The main context of this paper is organized as follows. In Section 2, the estimation methodology adopted and the data sources are briefly described. Section 3 presents the detailed estimation processes of CH_4 emissions from anthropogenic sources in China. In Section 4, the estimation results are systematically integrated, and the preliminary budgets of China's methane emissions at the national and regional level are discussed. Uncertainty analysis and comparison to prior estimates are also performed in this section. Some concluding remarks are made in Section 5.

2. Methodology and data sources

2.1. Estimation methods

In this study, CH_4 emissions from all the notable sources are considered, covering agricultural activities (i.e., enteric fermentation, manure management, rice cultivation, and field burning of crop residues), energy activities (i.e., coal mining, oil and natural gas leakage, and biomass combustion), and waste management (i.e., municipal solid waste landfill, industrial wastewater management, and domestic sewage management). The methodology used to estimate emissions from each activity is taken from IPCC [82]. Though the default CH_4 emission factors for different sources have been developed by IPCC [82], the factor of a specific activity may vary greatly between countries and regions. We review first the previous studies relevant to CH_4 emission factors of different sources, and then propose the national emission factors specifically suitable to the Chinese condition. In the case that specific emission factors are not available, the IPCC default emission

factors provided in IPCC [82] are adopted. For certain emissions whose direct evaluation is difficult, we make some sound assumptions based on recent studies for CH_4 emissions, as a preliminary approximation.

2.2. Data sources and regional information

Most of the relevant environmental resources and economic data are collected or derived from the official statistical yearbooks, such as China Agriculture Yearbook [83], China Energy Statistical Yearbook [84], China Environmental Statistical Yearbook [85], China Marine Statistical Yearbook [86], China Statistical Yearbook [87], China Statistical Yearbook for Regional Economy [88], and China Urban Construction Statistical Yearbook [89].

With regard to the administrative division, Mainland China consists of 31 regions at the provincial level, including 22 provinces, 5 autonomous regions (Inner Mongolia, Guangxi, Xinjiang, Ningxia, and Xizang) and 4 municipalities (Beijing, Shanghai, Tianjin and Chongqing, directly under the Central Government). Based on their geographical locations, all the 31 regions of China can be grouped into four areas [90], i.e., the Northeastern area (Heilongjiang, Jilin, and Liaoning,), the Eastern area (Beijing, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, and Hainan), the Central area (Shanxi, Henan, Anhui, Hubei, Hunan, and Jiangxi), and the Western area (Inner Mongolia, Shaanxi, Ningxia, Gansu, Xinjiang, Qinghai, Xizang, Sichuan, Chongqing, Guizhou, Yunnan, and Guangxi), as shown in Fig. 1. The northeastern, eastern, central and western areas contributed to 8.5%, 57.4%, 18.9%, and 15.2% of the national gross domestic product (GDP) in 2007, respectively.

Fig. 1. Mainland China in four areas.

Table 1
Emission factors of enteric fermentation (kg/head/year).

Category	Khalil et al. [64]	Yamaji et al. [34]	IPCC [82]	Zhou et al. [37]
Non-dairy cattle	44	–	47	54.21
Dairy cattle	44	–	61	65.25
Buffalo	50	56.3	55	72.92
Sheep	5	5.6	5	5.34
Goats	5	5.4	5	4.62
Camels	58	58	46	46
Pigs	1	1	1	1
Horses	18	18	18	18
Assess	10	10	10	10
Mules	10	10	10	10

3. Emission estimation

3.1. Enteric fermentation and manure management

China has a flourishing livestock production with a rapid increase in livestock numbers and with the largest meat and egg yields in the world. Normal digestive processes of the livestock such as cattle, sheep and camels always result in CH_4 emissions as a byproduct exhaled. Enteric fermentation refers to the fermentation process whereby microbes in the animals' digestive system ferment food [68]. Methane is also emitted from animal manure management anaerobically during storage and use. According to IPCC [82], CH_4 emissions from enteric fermentation and manure management can be calculated by

$$E_{methane} = \sum_i (P_i\, EF_i) \tag{1}$$

where $E_{methane}$ is CH_4 emissions from enteric fermentation or manure management, P is the number of livestock or poultry,

Table 2
Emission factors of manure management (kg/head/year).

g	CCCCS [66]				IPCC [82]			Zhou et al. [37]
	Cool	Temp.	Warm	Average	Cool	Temp.	Warm	
Non-dairy cattle	0.65	0.92	1.97	0.77	1	1	1	0.92
Dairy cattle	7.65	16.36	26.17	8.87	9–12	13–26	28–31	8.95
Buffalo	0.92	1.07	2.35	1.07	1	2	2	1.8
Sheep	0.10	0.15	0.20	0.1	0.1	0.15	0.2	0.1
Goats	0.11	0.17	0.22	0.13	0.11	0.17	0.22	0.13
Camels	1.28	1.92	2.56	1.28	1.28	1.92	2.56	1.28
Pigs	1.26	3.74	7.09	3.05	2	3–6	6–7	1.53
Horses	1.09	1.64	2.19	1.23	1.09	1.64	2.19	1.23
Assess	0.60	0.90	1.20	0.62	0.6	0.9	1.2	0.62
Mules	0.60	0.90	1.20	0.62	0.6	0.9	1.2	0.62
Chicken	0.012	0.018	0.023	0.016	0.01	0.02	0.02	0.015
Duck								0.01
Goose								0.02

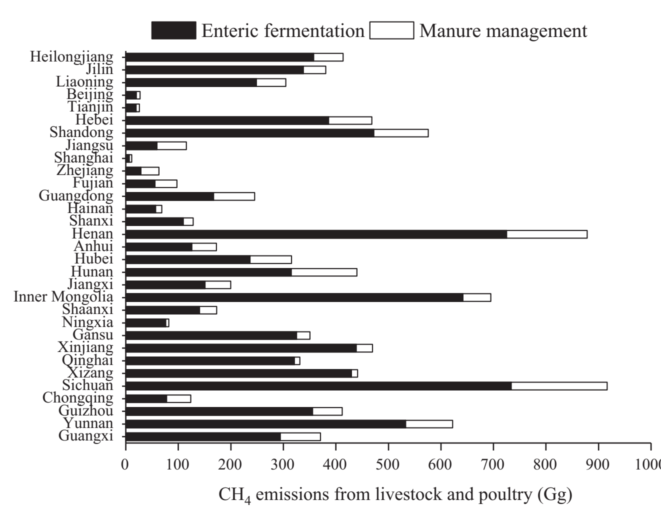

Fig. 2. Methane emissions from enteric fermentation and manure management by region.

EF is the emission factor of enteric fermentation or manure management, and *i* is the animal category.

The number of live stock and poultry by region and by animal category are available in China Agriculture Yearbook [83]. To determine the values of the emission factors involved in Eq. (1), we resort to the existent studies, as listed in Tables 1 and 2. Most of the emission factor values used in the present work are taken from Zhou et al. [37], which have been widely used to estimate the CH_4 emissions from enteric fermentation and manure management in China (e.g., [38,43,71]). The emission factor of manure

Table 3
Emission factors of rice cultivation by region (kg/ha^2/d).

Region	Northern	Southern			
	Single-harvest rice	Double-harvest early rice	Single-harvest rice	Double-harvest late rice	Single-harvest late rice
Growing period (d)	95–110 (102.5)	80–90 (85)	100–110 (105)	80–100 (90)	100–110 (105)
Heilongjiang	0.79				
Jilin	0.53				
Liaoning	0.88				
Beijing	1.26				
Tianjin	1.08				
Hebei	1.46				
Shandong	2				
Jiangsu		1.89	1.89	2.76	5.1
Shanghai		1.46	1.46	2.75	5.13
Zhejiang		1.69	1.69	3.45	5.52
Fujian		0.91	0.91	5.26	4.14
Guangdong		1.77	1.77	5.16	5.43
Hainan		1.58	1.58	4.94	4.98
Shanxi	0.63				
Henan	1.7				
Anhui		1.97	1.97	2.76	4.88
Hubei		2.06	2.06	3.9	5.54
Hunan		1.73	1.73	3.41	5.36
Jiangxi		1.82	1.82	4.58	6.23
Inner Mongolia	0.85				
Shaanxi	1.19				
Ningxia	0.7				
Gansu	0.65				
Xinjiang	1				
Xizang	0.65				
Sichuan		0.77	0.77	1.85	2.45
Chongqing		0.77	0.77	1.85	2.45
Guizhou		0.6	0.6	2.1	2.1
Yunnan		0.28	0.28	0.76	0.69
Guangxi		1.46	1.46	4.91	4.55

Note: Some of the double-harvest late rice (the excess part of double-harvest late rice over double-harvest early rice) is not preceded by early rice, which is counted as single-harvest late rice [43].

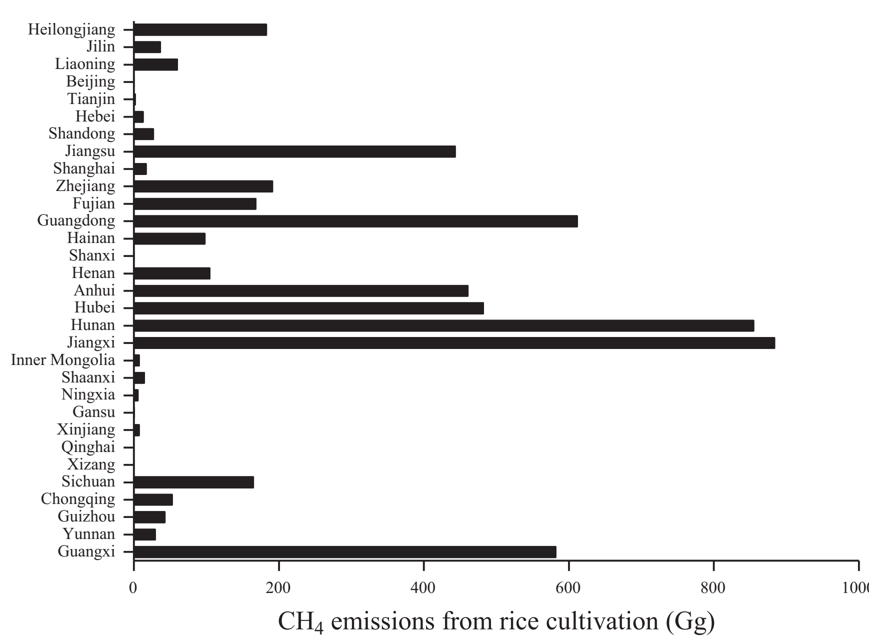

Fig. 3. Methane emissions from rice cultivation by region.

management for pigs provided in CCCCS [58], 3.05 kg/head/year, is adopted here, owing to the large difference between Zhou et al. [37] and other studies listed in Table 2.

The total CH_4 emission from enteric fermentation is estimated to be 8245 Gg, and that from manure management 1674 Gg in China 2007. Non-dairy cattle contributes the most in CH_4 emissions from enteric fermentation, accounting for 51.8% of the total, followed by the dairy cattle, buffalo, goats, sheep and pigs. Pigs, the major domestic livestock in China, accounted for 41.1% of the total livestock fed in 2007. Owing to the larger swine population, pigs contribute the most in CH_4 emissions from manure management, up to 80.2% of the total. The total emission from enteric fermentation and manure management is estimated to be 9919 Gg.

At the regional level, as displayed in Fig. 2, Sichuan and Henan are the top two regions with the largest CH_4 emissions from enteric fermentation and manure management. Furthermore, Sichuan (8.9% of the total), Henan (8.8%), Inner Mongolia (7.8%), Yunnan (6.5%), Shandong (5.7%), Xinjiang (5.3%), and Xizang (5.2%) are the 7 primary contributors of CH_4 emissions from enteric fermentation. Meanwhile, Sichuan and Henan account for respectively 10.9% and 9.2% of the total emission from manure management, followed by Hunan for 7.5%, Shandong for 6.2%, Yunnan for 5.3%, and Hebei for 4.9%.

3.2. Rice cultivation

China is the largest producer of rice grains with the world's second-largest area of rice paddies. Methane is produced through the anaerobic decomposition of organic matter in flooded rice paddies. The CH_4 emissions from Chinese rice paddies are of great significance in the regional and global CH_4 budget, which have motivated a large number of studies on emission estimation methods (e.g., [26,27,31–33,66]). Following a latest study of Fu and Yu [43], we employ

$$E_{methane} = \sum_{i,j}(A_{i,j}\ EF_{i,j}\ t_{i,j}) \tag{2}$$

to calculate the CH_4 emissions from the rice paddies. Here, $E_{methane}$ is CH_4 emissions from rice paddies; A is the cultivated rice area; EF the emission factor; t the rice growing period; and i and j the administrative region and rice season division (early, middle and late), respectively. The rice areas with various rice season divisions (early, middle and late) by region are available from China Agriculture Yearbook [83]. There is only single-harvest rice in Northern China, while double-harvest early rice, single-harvest rice and double-harvest late rice are cultivated in Southern China. Fu and Yu [43] compared different emission factors for rice cultivation in China and provided the CH_4 emission factors of each rice season by region suitable to the Chinese situation (see Table 3).

In 2007, the rice cultivation area in China was 28.9 million hectares and the yield of rice grain was 191.9 million tons [83]. The total emission from rice cultivation is estimated to be 5538 Gg, of which double-harvest late rice contributes 2225 Gg (40.2% of the total), single-harvest rice 1836 Gg (33.2%), and double-harvest early rice 827 Gg (14.9%).

As to the regional emissions shown in Fig. 3, Jiangxi contributes the most, of 16.0% to the overall emission, amounting to 883 Gg, followed by Hunan of 15.4%, Guangdong of 11.0%, Guangxi of 10.5%, Hubei of 8.7%, Anhui of 8.3%, and Jiangsu of 8.0%. The first 7 regions, among all the 30 regions, are responsible for 77.9% of the total emission.

3.3. Field burning of crop residues

Field burning of agricultural crop residues is a sizable source of agricultural CH_4 emissions in China. Straw is the major type of crop residue. For the calculation of CH_4 emissions from field burning of crop residues, a general estimation method can be described as

$$E_{methane} = \sum_{i,j}(P_{i,j} r_i f_{i,j} EF_i) \tag{3}$$

where $E_{methane}$ is CH_4 emissions from field burning of crop residues, P is crop production, r the straw/crop ratio, f the proportion of the straw field burned (%), EF the emission factor of field burning of straw, and i and j the crop type and provincial administrative division, respectively.

The crop types considered here include rice, wheat, corn, other grains, beans, tubers, cotton, oil-bearing crops, fiber crops, sugarcane, and sugar beet with the production data collected from China Agriculture Yearbook [83]. Comparable to the results of other previous studies, the straw/crop ratio adopted in this study is listed in Table 4. According to Liu et al. [96], on average 20.5% of the crop residues in China is processed directly through burning in the field. Wang and Zhang [91] further provided the proportion of straw field-burning by region in China 2006 through questionnaires so as to account for the actual regional circumstances (see Table 5). Similar to the study of Fu and Yu [43], we adopt the local data for the year of 2007 directly. The

Table 5
The proportion of straw field-burned in China.

Province	The proportion of the straw field burned (%)
Beijing, Tianjin, Hebei, Shanxi, Shandong, Henan, Shaanxi	16.5
Inner Mongolia, Liaoning, Jilin, Heilongjiang	11.8
Shanghai, Jiangsu, Zhejiang, Anhui, Fujian	31.9
Jiangxi, Hubei, Chongqing, Sichuan, Guizhou, Yunnan	10.7
Hunan, Guangdong, Guangxi, Hainan	32.9
Xizang, Gansu, Qinghai, Ningxia, Xinjiang	16.4

Table 4
The straw/crop ratio of various types of crop.

Crop type	Wang and Zhang [91]	Cao et al. [92]	Li et al. [93]	Yang et al. [94]	Li et al. [95]	Fu and Yu [43]	Present study
Rice	1	0.623	0.623	0.68	0.95	0.623	0.623
Wheat	1	1.366	1.366	0.73	1.28	1.366	1.366
Corn	2	2	2	1.25	1.25	2	2
Other grains	1	1	1	1.5	1.5	1	1
Beans	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Tubers	1	0.5	0.5	1	0.5	0.5	0.5
Oil-bearing crops	2	2	2	1.01	2	2	2
Cotton	3	3	3	5.51	3	3	3
Fiber crops	0.5	1.7		2	1.7	1.7	1.7
Sugar crops	–	0.1	0.25	–	0.1	0.1	0.1

emission factor of straw combustion, 2.7 g/kg, is adopted from Streets et al. [97], which has been widely used to estimate CH_4 emissions from field burning in China [91,92].

The CH_4 emission from field burning is estimated to be 335 Gg, of which field burning of grain straws (i.e., rice, wheat, corn straws) accounts for 80.7%. As shown in Fig. 4, Henan is the largest CH_4 emitter with an emission amount of 40 Gg, followed by Shandong, Anhui, Jiangsu, Hebei, Hunan and Guangxi. These regions have traditionally been the major crop-producing areas in China.

3.4. Coal mining

Intentional or unintentional release of CH_4 may occur during the extraction, processing and delivery of fossil fuels to the destination of final use. With coal meeting nearly 70% of China's primary energy demand, China had a total nationwide coal output of 2.52 billion tons in 2007 [84], the largest coal production in the world. Since methane is stored within the coal seams and the surrounding rock strata, heavy coal supply has resulted in a high growth rate of coalbed methane emissions emitted from mining operations [47–50]. In addition to emissions from coal mining, post-mining activities such as processing of coal also release methane. There are two types of coal mines, underground coal mines and surface coal mines, with distinctive emission factors. In China, over 95% of coal mines belong to underground coal mines [71]. Because of the great depth and high rank of China's coals, underground coal mines have higher CH_4 emissions than surface mines. Also, this special structure of coal mines results in more CH_4 fugitive emissions in China than in developed countries. China has been the world's leading emitter of coalbed methane [98].

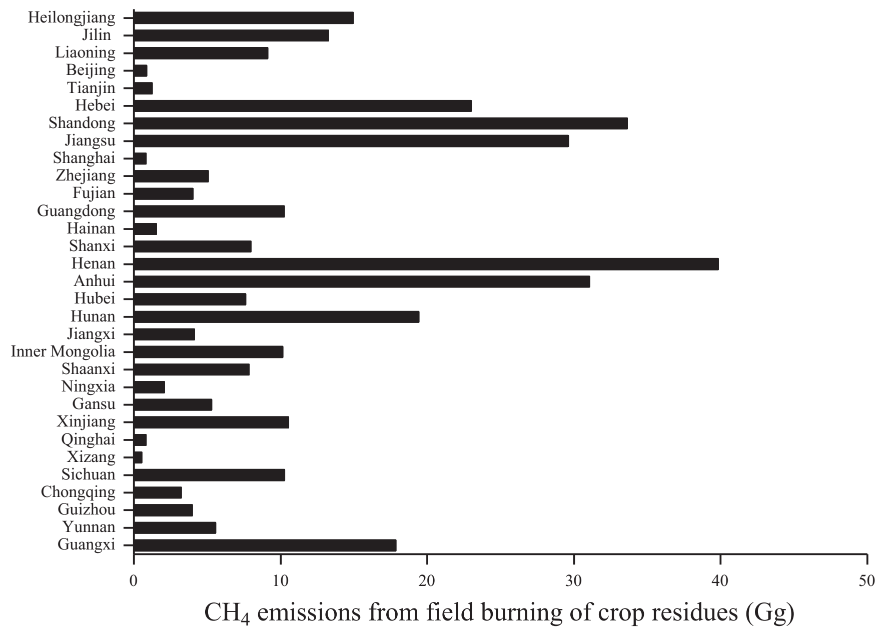

Fig. 4. Methane emissions from field burning of crop residues by region.

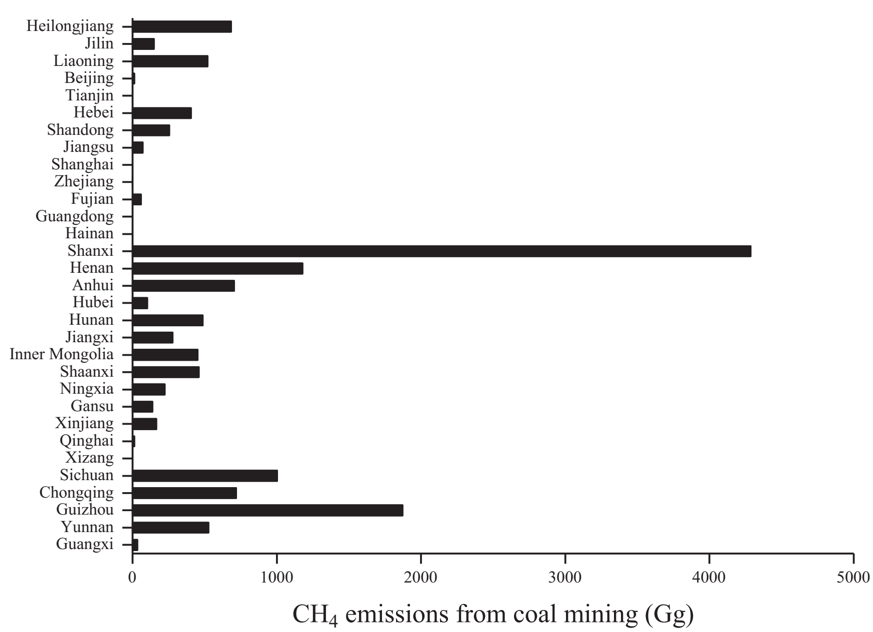

Fig. 5. Methane emissions from coal mining by region.

For the estimation of fugitive emissions from underground coal mining, Cheng et al. [50] provided the data of CH_4 emissions from coal mining by region in 2007 based on the report of the State Administration of Coal Mine Safety of China. Methane emissions from post-mining activities are estimated referring to the emission factor of CCCCS [66] and Zhang and Chen [71]. The total CH_4 emission from coal mining amounts to 14,785 Gg, of which 87.1% is from coal mining and 12.9% from post-mining activities. Underground mining of gas-rich coal mine is the primary source of these emissions.

In China, 27 out of all the 31 regions produced coal in 2007 [84]. Most coal is produced in the northern part of the Central and Western areas. Shanxi, Inner Mongolia, Shaanxi, Henan, and Shandong are the main coal producers. Fig. 5 displays the data of CH_4 emissions from coal mining by region. Although different regions have different kinds of coal resources and different concentrations of CH_4, the relationship between coal production and CH_4 emission is clear, most of the regions of high CH_4 emissions coincide with those of high coal production. Shanxi accounts for the largest part of CH_4 emissions with 29.0% of the total, followed by Guizhou (12.7%), Henan (8.0%), Sichuan (6.8%), Chongqing (4.9%), Anhui (4.8%), and Heilongjiang (4.6%). These 7 regions accounted for 70.6% of the total emission from coal mining in 2007. Owing to the complicated conditions on coal reserve and gas content, the CH_4 emissions in regions like Inner Mongolia show some discrepancies with their coal production [50].

3.5. Oil and natural gas system leakage

Methane is the principal component of natural gas and natural gas is often found in conjunction with petroleum deposits [68]. In both oil and natural gas systems, considerable fugitive CH_4 emissions come from equipment leaking, deliberate flaring and venting at production fields, oil processing, and natural gas storage and distribution. According to IPCC [82], fugitive CH_4 emissions from oil and natural gas systems can be calculated as

$$E_{methane} = \sum_i P_i EF_i \quad (4)$$

where $E_{methane}$ is CH_4 emissions from oil and natural gas systems; P is the activity level data of oil and natural gas systems (like oil well drill, oil production, oil refining, oil storage, oil transportation and oil sales; gas production, gas processing, gas transportation); EF the emission factor; and i the activity category.

The main emission sources in oil and natural gas systems considered in this study include: oil production (onshore fugitive emissions), oil production (offshore fugitive emissions), oil production (venting), and oil production (flaring) in oil systems; gas production (fugitive emissions), gas production (flaring), gas disposal (fugitive emissions), gas disposal (flaring), gas transportation (fugitive emissions), gas transportation (flaring), gas storage, and gas distribution in natural gas systems. To estimate the related CH_4 emissions, we resort to the works of Liu et al. [99], which provide the specific emission factors to calculate the CH_4 emissions from oil and natural gas systems in China on the basis of the local conditions and circumstances. Their data for emission factors are adopted directly in this study, as shown in Table 6. The data of crude oil output by region are mostly from China Energy Statistical Yearbook [84]. The data of offshore crude oil production by region are provided by China Marine Statistical Yearbook [86]. Natural gas production and consumption data by region are also available from China Energy Statistical Yearbook [84].

The total output of crude oil in China is 186 million tons in 2007 [84], 18 out of 31 regions produce crude oil, and about 73.8% of

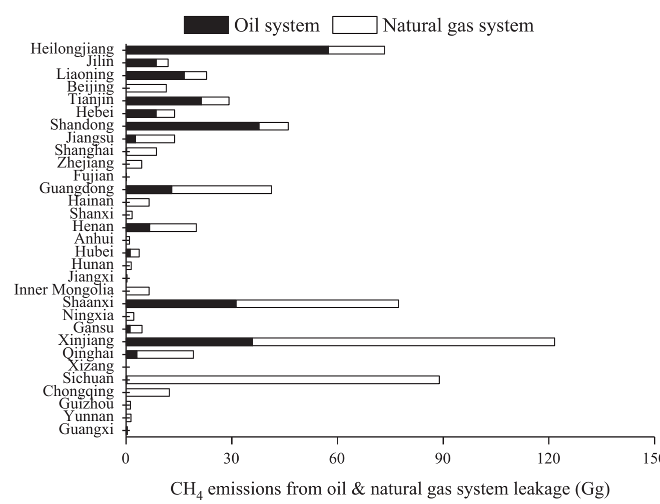

Fig. 6. Methane emissions from oil and natural gas system leakage by region.

Table 6
Emission factors of oil and natural gas system leakage.

Sources	Emission factor	Unit
Oil systems		
Oil production (onshore fugitive emissions)	3.00E−04	Gg/1000 m^3 oil production
Oil production (offshore fugitive emissions)	5.90E−07	Gg/1000 m^3 oil production
Oil production (venting)	8.55E−04	Gg/1000 m^3 oil production
Oil production (flaring)	2.95E−05	Gg/1000 m^3 oil production
Natural gas systems		
Gas production (fugitive emissions)	3.01E−03	Gg/MM m^3 gas production
Gas production(flaring)	8.80E−07	Gg/MM m^3 gas production
Gas disposal (fugitive emissions)	2.50E−04	Gg/MM m^3 gas production
Gas disposal (flaring)	2.40E−06	Gg/MM m^3 gas production
Gas transportation (fugitive emissions)	4.27E−04	Gg/MM m^3 gas marketable gas
Gas transportation (flaring)	1.80E−04	Gg/MM m^3 gas marketable gas
Gas storage	4.15E−05	Gg/MM m^3 gas marketable gas
Gas distribution	1.80E−03	Gg/MM m^3 gas utility sales

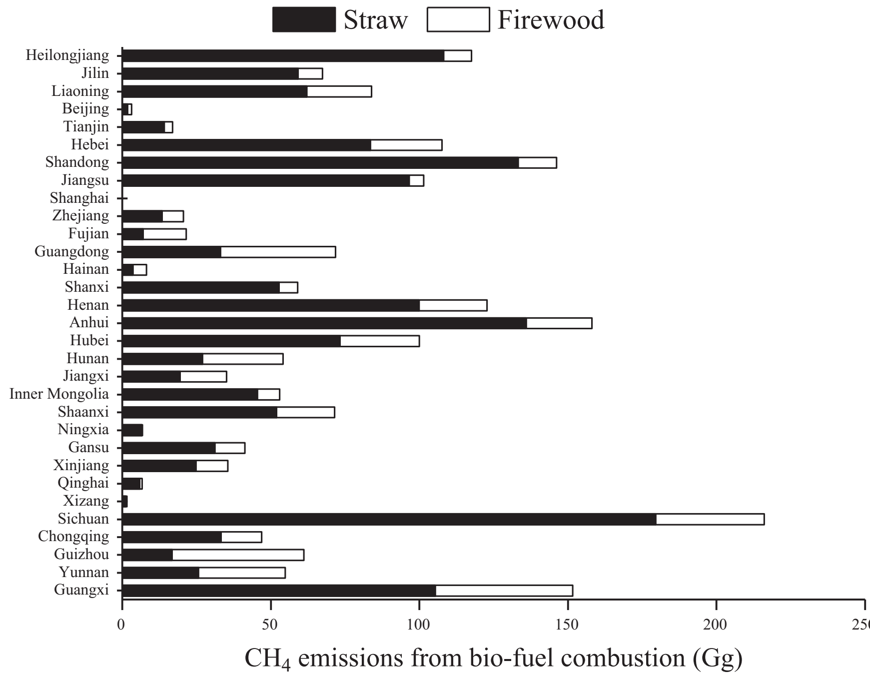

Fig. 7. Methane emissions from bio-fuel combustion by region.

China's domestic crude oil is produced by the 5 primary regions of Heilongjiang, Shandong, Xinjiang, Shaanxi and Tianjin. The fugitive emission from oil systems is estimated to be 246 Gg in 2007, of which 22.0% comes from onshore fugitive emissions and 75.4% from venting. On a regional basis, Heilongjiang accounts for 23.4% of the total emission, followed by Shandong for 15.3%, Xinjiang for 14.6%, Shaanxi for 12.7% and Tianjin for 8.7%. The detailed results are shown in Fig. 6.

Meanwhile, the total output of natural gas was 69.2 billion cubic meters in 2007 [84], 23 out of all the 31 regions produce natural gas. Most gas fields are located in the Western area of China, such as Xinjiang, Shaanxi, and Sichuan. The estimated CH_4 emission from natural gas systems is 401 Gg, of which gas production (fugitive emissions) is the largest emission source (208 Gg, 52.0% of the total), followed by gas distribution (129 Gg, 32.1%) and gas transportation (fugitive emissions) (31 Gg, 7.6%).

Fig. 6 also gives the emission estimates on a regional basis for the year of 2007. The three regions of Sichuan (89 Gg), Xinjiang (86 Gg), and Shaanxi (46 Gg) are responsible for 55.0% of the total national-wide emission. Guangdong and Qinghai also contribute 7.1% and 4.0%, respectively.

3.6. Bio-fuel combustion

In rural China, straw and firewood are the two primary bio-fuels for daily cooking and domestic heating. Incomplete combustion of biomass resources releases GHGs such as CH_4 [51,100]. The formula for estimating CH_4 emissions from the burning of straw and firewood in rural households can be expressed as,

$$E_{methane} = B_{straw}EF_{straw} + B_{firewood}EF_{firewood} \tag{5}$$

where $E_{methane}$ is CH_4 emissions from bio-fuel combustion; B_{straw} and $B_{firewood}$ are the consumption amount of straw and firewood, respectively; and EF_{straw} and $EF_{firewood}$ are the emission factors of straw and firewood combustion, respectively.

The data of non-commercial energy consumption for rural residents by region in 2007 covering straw and firewood are available in China Energy Statistical Yearbook [84]. Zhang et al. [100] published a database for emission factors of GHGs from rural household stoves in China, which have been widely used to estimate the GHG emissions from rural energy consumption [52,101,102]. Therefore, the emission factors of straw and firewood

Table 7
Classification of solid waste disposal sites and CH_4 correction factors by region.

Region	Managed-anaerobic (%)	Unmanaged-deep (> 5 m waste) (%)	Unmanaged-shallow (< 5 m waste) (%)	*MCF*
Heilongjiang	26.3	55.3	18.4	0.78
Jilin	17.4	62.0	20.6	0.75
Liaoning	23.6	57.3	19.1	0.77
Beijing	49.2	38.1	12.7	0.85
Tianjin	54.2	34.4	11.4	0.86
Hebei	41.8	43.7	14.5	0.83
Shandong	49.5	37.9	12.6	0.85
Jiangsu	82.1	13.4	4.5	0.95
Shanghai	0.9	74.3	24.8	0.7
Zhejiang	33.7	49.7	16.6	0.8
Fujian	36.8	47.4	15.8	0.81
Guangdong	61.8	28.6	9.6	0.89
Hainan	33.7	49.7	16.6	0.8
Shanxi	35.8	48.2	16.0	0.81
Henan	46.5	40.1	13.4	0.84
Anhui	34.5	49.1	16.4	0.8
Hubei	32.8	50.4	16.8	0.8
Hunan	62.1	28.4	9.5	0.89
Jiangxi	24.3	56.8	18.9	0.77
Inner Mongolia	25.6	55.8	18.6	0.78
Shaanxi	0	75.0	25.0	0.7
Ningxia	24.5	56.6	18.9	0.77
Gansu	25.3	56.0	18.7	0.78
Xinjiang	0	75.0	25.0	0.7
Qinghai	58.8	30.9	10.3	0.88
Xizang	0	75.0	25.0	0.7
Sichuan	46.4	40.2	13.4	0.84
Chongqing	70.2	22.3	7.5	0.91
Guizhou	5.7	70.7	23.6	0.72
Yunnan	18.9	60.8	20.3	0.76
Guangxi	27.8	54.1	18.1	0.78

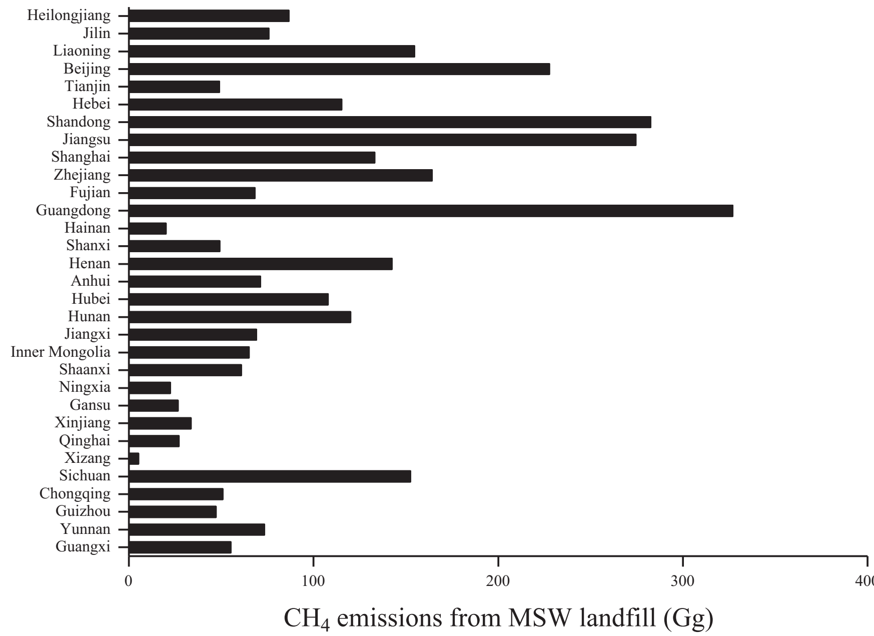

Fig. 8. Methane emissions from MSW landfill by region.

fuel combustion in [100], 4.56 g CH_4/kg straw and 2.7 kg CH_4/kg firewood, are adopted.

The total CH_4 emission from straw fuel combustion in 2007 was estimated as 1550.3 Gg. As shown in Fig. 7, the leading regions for CH_4 emissions from straw combustion are Sichuan (11.6% of the total), Anhui (8.8%), Shandong (8.6%), Heilongjiang (7.0%), Guangxi (6.8%), Henan (6.4%), and Hebei (5.4%). These 7 regions contribute 60.8% of the total emission. The CH_4 emission from firewood burning is estimated to be 491.9 Gg. Among all the 31 regions, the 7 regions of Guangxi, Guizhou, Guangdong, Sichuan, Yunnan, Hubei, and Hunan with abound forest biomass resources are responsible for 50.7% of the total emission. Shaanxi, Henan, Liaoning, Anhui, and Hebei are the secondary regions to emit CH_4 by firewood burning. The detailed information is displayed in Fig. 7.

3.7. Municipal solid waste landfill

Increasing and rapid urbanization has put significant pressures on waste management in urban areas of China. The total amount of MSW collected and transported was 152.1 million tons in 2007 [89]. MSW disposal in China is predominately by means of landfill, due to its cost-effectiveness and flexibility to handle the amount and type of waste. Methane gas is a by-product of landfilling MSW from the anaerobic decomposition of various organic matters (e.g., kitchen garbage, paper, and wood). Most of the generated methane in China is directly emitted into the atmosphere. According to the Tie 1 methodology in IPCC [82], the CH_4 emissions from the MSW landfills are calculated by

$$E_{methane} = MSW_T \cdot MCF \cdot DOC \cdot DOC_F \cdot F \cdot \tfrac{16}{12} \qquad (6)$$

where $E_{methane}$ is CH_4 emissions from MSW landfill; MSW_T is the total MSW disposed to landfills; MCF the CH_4 correction factor according to the method of disposal and depth available at landfills; DOC the fraction of degradable organic carbon in the MSW; DOC_F the fraction of total DOC that actually degrades; F the fraction of CH_4 in landfill gas (default value is 0.5); and 16/12 the conversion ratio (CH_4/C).

The quantity of MSW disposed to landfills by region in 2007 is provided in China Urban Construction Statistical Yearbook [89]. Specific values of MCF depend on the types of MSW landfill practices

Table 8
Average BOD_5/COD ratios for the municipal wastewater treatment plants by region.

Region	Average influent BOD_5/COD ratio	Average effluent BOD_5/COD ratio
Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia	0.46	0.28
Heilongjiang, Jilin, Liaoning	0.45	0.31
Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Anhui, Jiangxi	0.42	0.26
Henan, Hubei, Hunan	0.48	0.34
Guangdong, Guangxi, Hainan	0.49	0.32
Sichuan, Chongqing, Guizhou, Yunnan, Xizang	0.51	0.31
Shaanxi, Ningxia, Gansu, Xinjiang, Qinghai	0.44	0.29

[82]. Taking into consideration the way waste is managed and the effect of site structure and management practices on CH_4 generation, Du [57] has provided detailed regional MCF values in China (see Table 7). MSW composition in China is dominated by a high organic and moisture content, as the kitchen waste takes a high fraction of the urban solid waste [103], and thus, the estimated DOC data with 0.151 for nationwide average in Ma and Gao [60] is adopted. As the biodegradation of DOC does not occur completely over a long period of time, the value of 0.5 for DOC_F is adopted in this study following the recommendation in Ma and Gao [60].

The total estimated CH_4 emission from MSW landfill amounts to 3157 Gg. Methane emissions from MSW landfill by region are shown in Fig. 8. As the largest province of urban population in China, Guangdong produces the largest quantities of municipal solid waste, and has the largest CH_4 emission from MSW landfill with an emission amount of 327 Gg, accounting for 10.4% of the total. Next, Shandong, Jiangsu, and Beijing each emit more than 200 Gg CH_4.

3.8. Wastewater management

Methane is considered as the most important GHG emitted from wastewater management [104]. Theoretical approach recommended by IPCC [82] is commonly applied to estimate the CH_4 emissions from wastewater management, which presumes that the entire degradable organic fraction removed under anaerobic condition is converted into

methane. Degradable organic fraction in wastewater is the main factor to determine the extent of CH_4 emissions, which is commonly expressed in terms of chemical oxygen demand (COD) in Chinese environmental statistics [85].

The CH_4 emissions from industrial wastewater can be calculated by

$$E_{methane} = COD \cdot EF \cdot MCF \tag{7}$$

where $E_{methane}$ is CH_4 emissions from industrial wastewater management; *COD* (chemical oxygen demand) represents the organic loading removed; *EF* the specific emission factor (g CH_4/g COD removed); and *MCF* the fraction of COD in wastewater treated anaerobically as a CH_4 emission correction factor.

The data of chemical oxygen demand (COD) removed through industrial wastewater treatment utility and discharged into water bodies by region are provided in China Environmental Statistical Yearbook [85]. The default emission factor for the COD removed, 0.25 g CH_4/g COD removed, is adopted from IPCC [82] directly. Generally there are two approaches to assign *MCF* values for wastewater management: one is the COD removed through the wastewater treatment utility, and the other is wastewater discharged into water bodies directly [82]. The *MCF* value for the COD removed through industrial wastewater treatment utility in China is assumed to be 0.458 as provided in Ma and Gao [60]. The default *MCF* value for the COD discharge, 0.1, is adopted from IPCC [82].

For the estimation of CH_4 emissions from sewage management, the formula can be simply expressed as

$$E_{methane} = BOD_5 \cdot EF \cdot MCF \tag{8}$$

where $E_{methane}$ is CH_4 emissions from domestic sewage management; BOD_5 (biochemical oxygen demand) represents the organic loading removed; *EF* the specific emission factor (g CH_4/g BOD_5 removed); and *MCF* the methane correction factor.

Since the regional BOD_5 data in China cannot be obtained directly, we can calculate the organic loading removed on basis of the COD contents in domestic sewage and the BOD_5/COD ratios by region [60]. The COD removed through municipal wastewater treatment plants by region (2009 data) and discharged directly into water bodies (2007 data) by region are available in Ma [61] and China Environmental Statistical Yearbook [85], respectively. Song [62] reported the average influent and effluent BOD_5/COD ratios for municipal wastewater of the treatment plants by region in China, as shown in Table 8. The default emission factor for the BOD_5 removed, 0.6 g CH_4/g BOD_5 removed, is adopted from IPCC [82]. The *MCF* value (0.165) for the BOD_5 removed through municipal wastewater treatment plant source from Ma [60] and the default *MCF* value (0.1) for the BOD_5 discharged into water bodies are adopted from IPCC [82].

The total estimated CH_4 emission from wastewater management amounts to 2140 Gg, of which industrial wastewater management contributes 1577 Gg, and domestic sewage management 564 Gg. On a regional basis, the main emitters of CH_4 from industrial wastewater management are Shandong (13.7% of the total), Fujian (10.6%), Zhejiang (9.2%), Jiangsu (8.4%), Henan (8.2%), Guangxi (6.0%), Hebei (4.5%), Sichuan (4.4%) and Guangdong (4.4%), which are the main industrial bases for paper, sugar, alcohol, food manufacturing and processing in China. Meanwhile, the daily living of urban residents and the commercial and service activities in the urban areas discharge a large amount of domestic sewage, Guangdong (9.3% of the total), Jiangsu (8.1%), Shandong (8.0%), Zhejiang (6.9%), Henan (5.5%),,and Hubei (5.1%) are the top 6 emitters of CH_4 from sewage management. Detailed results are shown in Fig. 9.

4. Results and discussion

4.1. Methane emissions by source

CH_4 emissions by source in China in the year 2007 are summarized in Table 9. The total CH_4 emission amounts to 38.6 Tg, which is 29.2 kg per-capita for a total population of 1321.3 million as of the end of 2007. As shown in Fig. 10, the total CH_4 emission from anthropogenic sources in China was much larger than those in most Annex I countries and European Community in 2007 according to the national CH_4 emission data

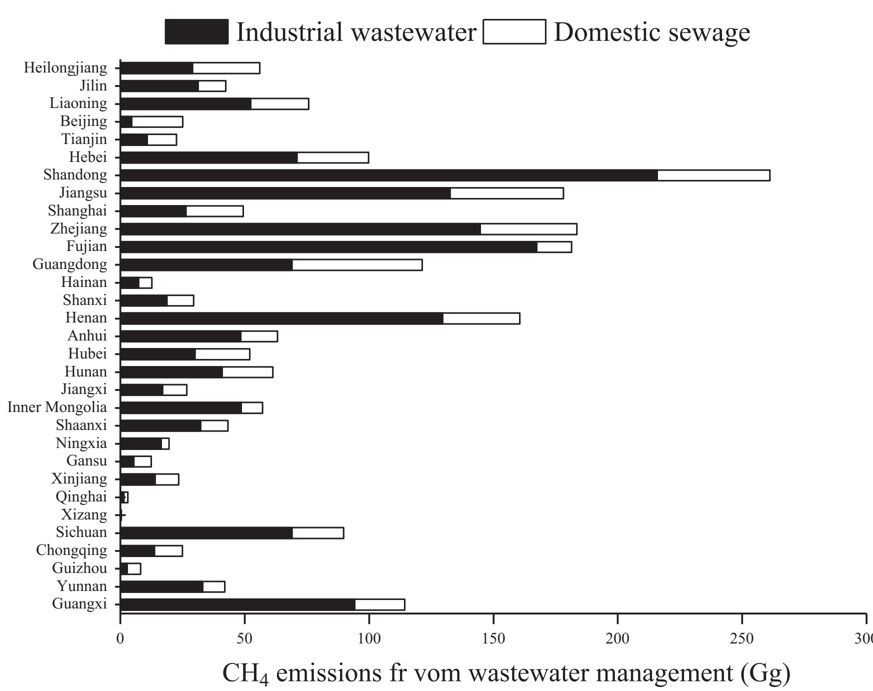

Fig. 9. Methane emissions from wastewater management by region.

Table 9
Anthropogenic methane emission by source in China.

Emission source	Methane emissions (Gg)	Fraction (%)
1. Agricultural activities	15,792	40.9
Enteric fermentation	8245	21.4
Manure management	1674	4.3
Rice cultivation	5538	14.4
Field burning of agricultural residues	335	0.9
2. Energy activities	17,474	45.3
Coal mining	14,785	38.3
Oil system leakage	246	0.6
Natural gas system leakage	401	1.0
Straw combustion	1550	4.0
Firewood combustion	492	1.3
3. Waste management	5298	13.8
MSW landfill	3157	8.2
Industrial wastewater	1577	4.1
Domestic sewage	564	1.5
Total	38,564	100.0

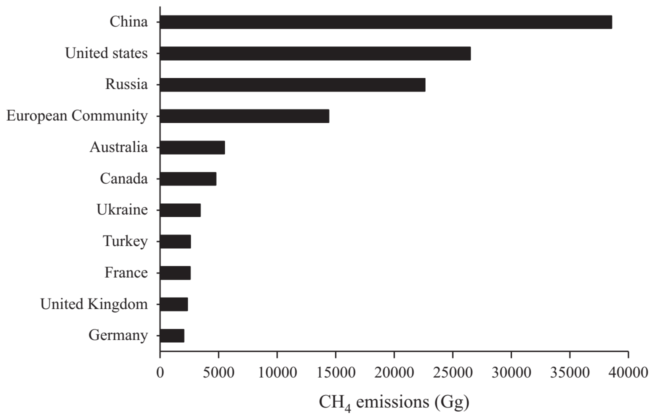

Fig. 10. Total anthropogenic methane emissions in China and representative countries.

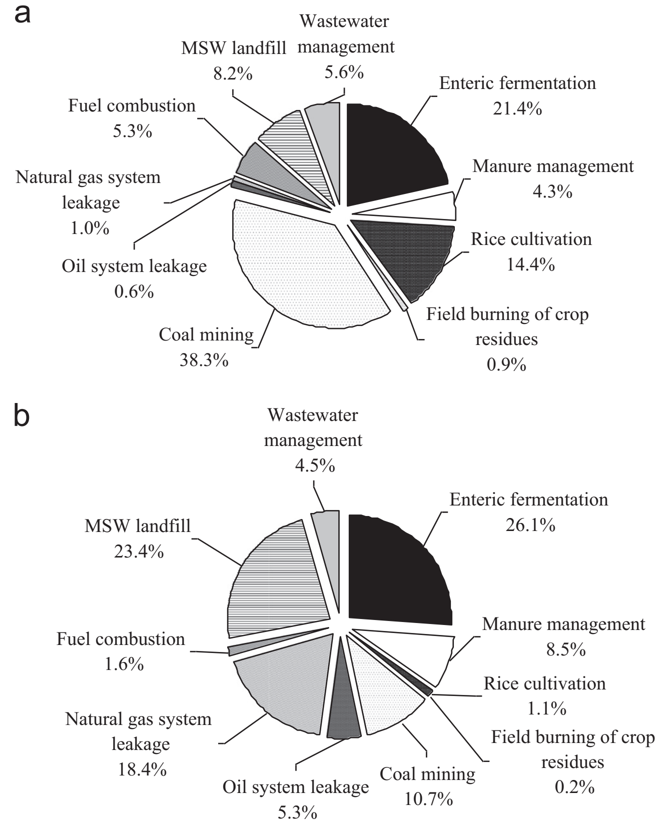

Fig. 11. Emission structures in China and USA in 2007.

(excluding emissions/removals from land use, land-use change and forestry) reported in UNFCCC [105], and China can be considered as the largest CH_4 emitter in the world.

The contribution of CH_4 to the total GHG emissions can be estimated by expressing the emission of CH_4 in CO_2-equivalent units, and the indicator of Global Warming Potential (GWP) based upon simplified radiation models has been used to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to CO_2 in terms of CO_2 equivalents [18]. IPCC [18] recommended certain values for the GWPs of CH_4 over different time horizons. It follows that the CH_4 emission in China 2007 was equivalent to 964.1 Mt CO_2-eq with the GWP factor of 25 over a time horizon of 100 years and 2776.6 Mt CO_2-eq with the GWP factor of 72 over 20 years, respectively. Recently, as an alternative way to quantify CO_2-equivalent, the global thermodynamic potential (GTP) indicator derived from global exergy analyses [106–108] has also been applied to evaluate GHG emissions [71–74,109–114], The GTP represents the thermodynamic departure between the emission and its global environment. The standard chemical exergy intensities of CH_4 and CO_2 are 51.98 kJ/g and 0.45 kJ/g, respectively, and the corresponding GTP factor of CH_4 is 115.51. Based on this GTP factor, the CH_4 emission in China 2007 corresponded to 4454.5 Mt CO_2-eq.

China generated around 6499.1 Mt CO_2 emissions (excluding emissions from land use change) in 2007 [115]. It is worth noting that even by the commonly referred lower IPCC GWP factor of 25, the total CH_4 emission in China 2007 was 14.8% of the total CO_2 emission, and the total CH_4 emission was equivalent to 42.7% and 68.5% of the total CO_2 emission in China by the GWP factor of 72 and the GTP factor of 115.51, respectively. Obviously, the CH_4 emission of 964.1 Mt CO_2-eq is greater in magnitude than the total amounts of nationwide CO_2 emissions in some developed countries, like England (547.5 Mt), Canada (591.4 Mt), and Germany (833.9 Mt) in 2007 [105]. This comparison highlights the unique importance of China's CH_4 emissions from anthropogenic sources in the national and the global GHG emission inventories.

Regarding the emission sources, energy activities are the largest emission source with the emission amount of 17,474 Gg, responsible for 45.3% of the total. Among the emission of energy activities, the largest amount of 14,785 Gg comes from coal mining. Agricultural activities (mainly from enteric fermentation and rice cultivation) contribute a comparable share of 40.9%. Waste management also emits 5298 Gg CH_4 (13.7% of the total). Consequently, among all the 11 specific emission sources, coal mining, enteric fermentation and rice cultivation essentially determine the CH_4 emission profile of China.

China and USA are the leading emitters of CH_4 in the world. Considering the same contributors, USA emitted 25.7 Tg CH_4 in 2007, corresponding to about 98.4% of the total CH_4 emission reported in EPA [116]. In comparison, China emitted 1.5 times CH_4 from anthropogenic sources. If we take demographic factors into account, the conclusion will be very different. USA had a total population of 303.82 million as of the end of 2007, and thus, its methane emission per-capita is 84.7 kg, 2.9 times that of China. Displayed in Fig. 11 is a comparison of the emission shares for key source categories in China and USA. As shown in Fig. 11(a) for the main emission contributors in China, coal mining contributes 38.3% of the total, followed by enteric fermentation 21.4%, rice cultivation 14.4%, and landfills 8.2%. In contrast to the emission structure of China, enteric fermentation and MSW landfill are the

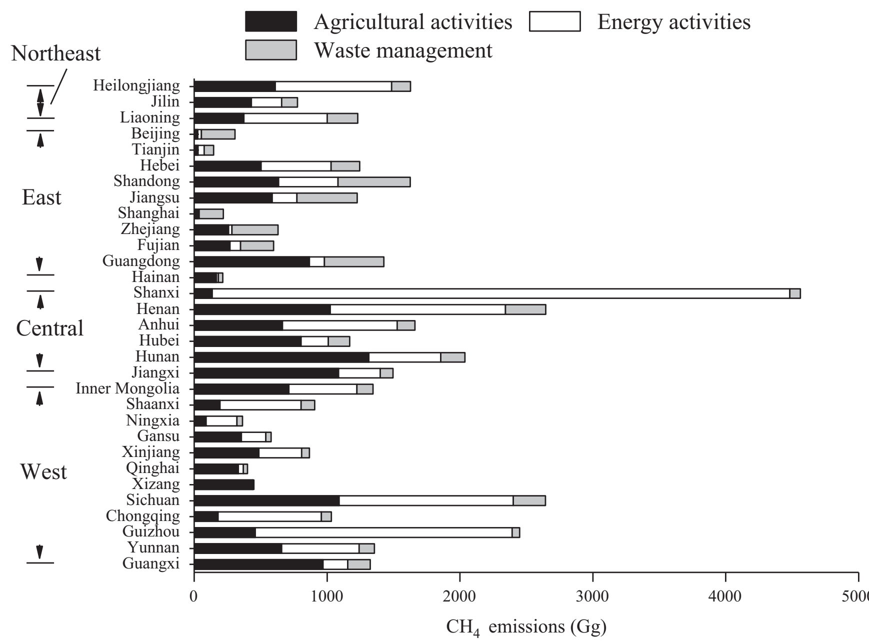

Fig. 12. Methane emissions by region.

top two sources in the US inventory shown in Fig. 11(b), accounting for 26.1% and 23.4% of the total, respectively. Meanwhile, CH_4 emission from rice cultivation in USA accounts for a very small proportion (only 1.1% of the total). Prominently, fugitive emissions from natural gas and oil systems contribute 18.4% and 5.3% of the total emission in USA, respectively, much higher than the shares of those emissions in China. Coal mining contributes a relatively small portion of 10.7% to the whole emission inventory of USA.

4.2. Methane emissions by region

The geographic distribution of CH_4 emission in China has significant regional differences. Fig. 12 presents the CH_4 emission by region in 2007. Shanxi is the largest emitter with an emission amount of 4560 Gg, 11.8% of the national total CH_4 emission, mainly due to the massive fugitive emissions from coal mining. The four regions of Henan, Sichuan, Guizhou, and Hunan also generate very large amounts of CH_4 emissions, respectively from 2037 Gg to 2646 Gg accounting for more than 5.0% of the total, owing to massive CH_4 emissions from coal mining and agricultural activities. Heilongjiang and Anhui contribute respectively 4.2% and 4.3% of the total. On the contrary, the least emissions occur in Tianjin, Hainan, Shanghai, Beijing, and Ningxia, ranging from 147 Gg to 365 Gg, less than 1.0% of the total. Furthermore, the Western area and the Central area generate respectively 13.7 and 13.6 Tg CH_4 emissions, accounting for 35.6% and 35.2% of the total nationwide emission, followed by the Eastern area (19.8%) and the Northeastern area (9.4%).

As to the emission composition by region shown in Fig. 12, agricultural activities are the largest emission sources in 16 regions, contributing about 40%–80% of the emissions in these regions, and particularly 98.4% in Xizang. Emission compositions are different in the 11 regions, i.e. Shanxi, Guizhou, Chongqing, Shaanxi, Ningxia, Anhui, Heilongjiang, Liaoning, Henan, Sichuan, and Hebei, where energy activities are the leading source of CH_4 emissions, mainly due to coal mining. For instance, fugitive emissions account for 95.3% of the total emission in Shanxi. Meanwhile, in the four regions of Beijing, Tianjin, Zhejiang, and Shanghai, waste management is the largest emission source; specifically, it contributes particularly 82.1% and 82.9% of the total emissions in Beijing and Shanghai, respectively.

Emission per-capita, as the ratio of the regional emission to the census population, is an important indicator to reflect the emission level in a region. Fig. 13 presents the emission per-capita by region. Xizang and Shanxi are the top two regions for the emission per-capita with the amounts of 1578.0 kg and 134.4 kg, followed by Qinghai of 72.5 kg, Guizhou of 65.1 kg, Ningxia of 59.7 kg, and Inner Mongolia of 55.9 kg. Heilongjiang and Xinjiang have emissions per-capita over 40 kg. The regions in the Eastern area such as Beijing, Tianjin, Hebei, Shandong, Shanghai, Jiangsu, Zhejiang, Fujian and Guangdong all have emissions per-capita below 20 kg. Moreover, Shandong and Guangdong contribute only 4.2% and 3.7% of the national total CH_4 emission, but account for 7.2% and 7.3% of the total census population of China, respectively. It is shown that the emission per-capita has a manifest regional gap between the eastern coastal regions and the western and central inland regions.

Emission intensity, defined as the regional emission per Yuan of regional GDP, indicates the level of environmental impact of a regional economy. Fig. 14 shows the emission intensity by region. Xizang has the largest emission intensity of 13.1 g/Yuan. The emission intensities of Guizhou (8.9 g/Yuan) and Shanxi (8.0 g/Yuan) are also much higher than those of the other regions. Qinghai and Ningxia are the next two regions with emission intensities of 5.1 g/Yuan and 4.1 g/Yuan, respectively. Notably, some western and central regions have high emission amounts with low industrial output values. For instance, Guizhou and Shanxi contribute only 1.0% and 2.1% to the total GDP, but share 6.4% and 11.8% of the total CH_4 emission of China, respectively. In contrast, the eastern regions such as Beijing, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian and Guangdong have the lowest emission intensities (all less than 1.0 g/Yuan). A marked difference between the eastern regions and the other regions can also be found from the emission intensity distribution.

4.3. Uncertainties and comparison to prior estimates

An emission inventory is always made on the basis of available knowledge, available data, emission factors, models, etc. [82]. Till now, there are two official GHG emission inventories of China published by the government, i.e., the first official GHG emission inventory of China

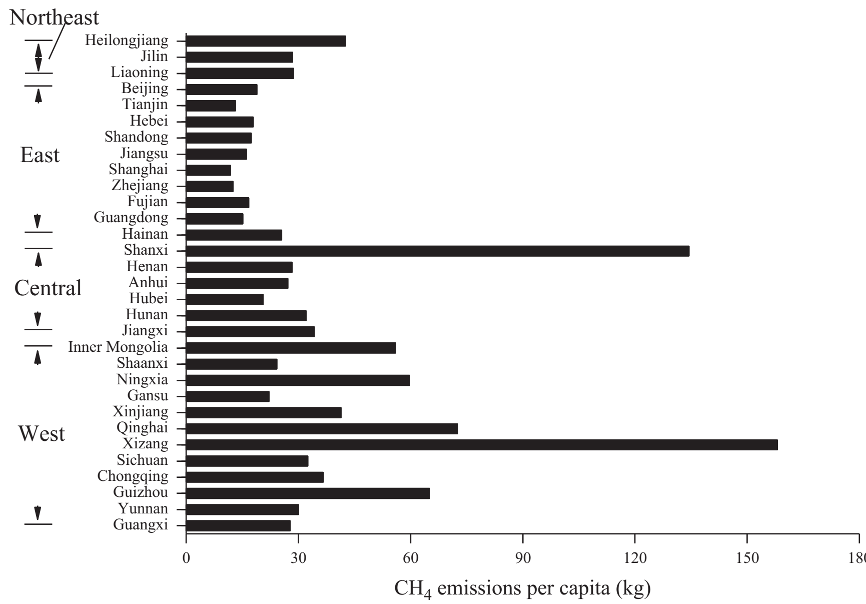

Fig. 13. Methane emission per-capita by region.

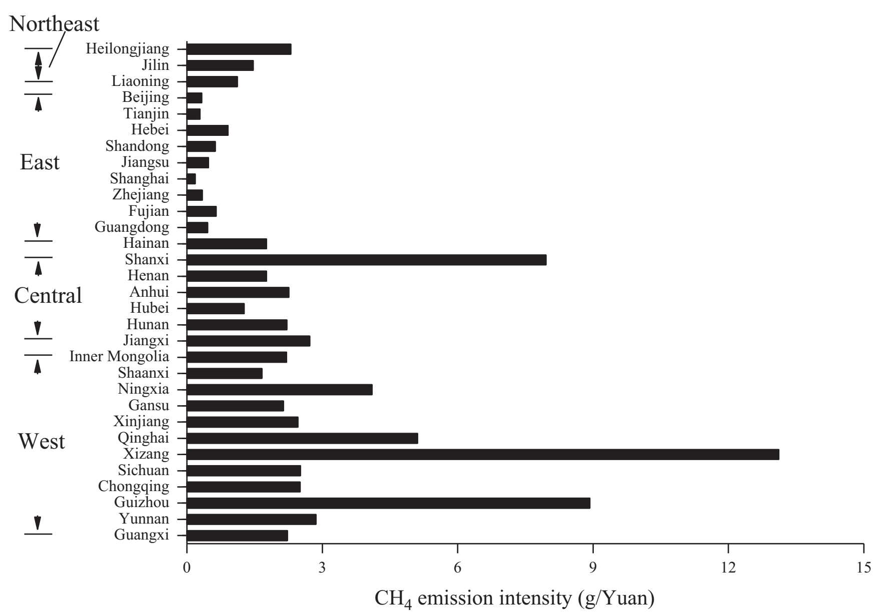

Fig. 14. Methane emission intensity by region.

for the year 1994 [19] and the latest official National GHG Inventory of China for 2005 [20]. However, no detailed regional emission information is provided in the national inventory. While this article presents a more complete and comprehensive evaluation of China's CH_4 emissions than other studies by totaling all regional emission inventories based on the latest statistical data and research literatures available, it unavoidably includes several areas of uncertainty in the estimates of each source category, as mentioned in IPCC [82] and many other reports [20,43,68].

Compared to CH_4 emissions, CO_2 emissions are highly sensitive to energy activities due to the dominated contributions of fossil fuel combustion [9,12–15]. On the contrary, the major sources of China's CH_4 emissions are coal mining, enteric fermentation, rice cultivation and waste management. As to the CH_4 emissions from energy activities, some emission sources are not incorporated into the estimates due to methodological and data limitations. Data uncertainty in China's coalbed methane emission statistics may be significant but is difficult to quantify [50]. In addition, the emissions from abandoned mines are not incorporated in this study, with the amount of 127.4 Gg in 2005 reported in SNCCCC [20]. Zhang and Chen [71] reported a result of 19.4 Tg CH_4 emissions from coal mining in 2007 based on simplified emission factors, much larger than 14.8 Tg in this study. The uncertainties of emission estimates of oil and gas system leakage are also associated with the completeness of the activity data and the inadequate evaluation of emission factors [99]. However, there are very limited studies at present with regard to CH_4 emissions from oil and gas system leakage in China. The CH_4 emission from fossil fuel

combustion in China is excluded in the national inventory. Zhang and Chen [71] reported that the CH_4 emissions of this part are less than 100 Gg . The results of CH_4 emissions from biomass combustion are sensitive to changes in regional emission factors, and there is uncertainty of estimation from the adoption of a unified emission factor. CCCCS [66] and Yue et al. [69] used the emission factors of 4.85 g CH_4/kg straw and 3.14 kg CH_4/kg firewood to estimate the emissions from bio-fuel combustion, higher than the emission factors used in this study. As a consequence, the estimated emissions from energy activities are likely to be lower than the real emissions.

Although energy-related CH_4 emissions contribute important shares in most energy production regions, non-energy related emissions also take a comparable share and account for more than half of the total CH_4 emissions in some eastern coastal regions. As to the CH_4 emissions from livestock in the agricultural sector, on one hand, the uncertainties of the estimates stem from the activity data [20] such as statistic errors. The CH_4 emissions are always not estimated by considering the life cycles of meat animals in most existing reports [37,43], and the uncertainty contributed by statistical data is no less than $\pm 10\%$ [43]. On the other hand, the emission factors used in this study give rise to uncertainties. For instance, the emission factors of manure management are not classified according to temperature at the provincial level. The methods to estimate CH_4 emissions from rice cultivation also entail significant uncertainty. We do not include the emissions from winter-flooded fields during rice non-growing periods due to data availability. According to SNCCCC [20], the emission from winter-flooded paddy fields was 1109 Gg in 2005. Uncertainties in emissions from field burning of agricultural residues are associated with the emission factors and the straw/crop ratio adopted, though this part is relatively small in this study. Therefore, this article is also likely to underestimate the emissions from agricultural activities [43].

The uncertainties in the inventory for waste management are originated from relevant methods and parameter selection. Uncertainties in the estimation of CH_4 emissions from municipal solid waste landfill are due to in large part the IPCC default method used, which cannot describe varying gas generation rates over the lifetime of the landfill relative to the First Order Decay modeling [59,82]. In addition, owing to data availability, the CH_4 emissions from simple landfill, deposit landfill, and MSW incineration, etc., are excluded, which results in a high degree of uncertainty. In 2007, only 62.3% of the municipal solid waste in China was disposed in sanctity landfill [89]. As to the estimation of CH_4 emissions from industrial wastewater management, uncertainty mainly comes from the selection of the emission correction factor due to the lack of information on regional wastewater statistics for industrial sub-sector. The uncertainties of the emissions from domestic sewage management are mainly associated with the actual organic loading removed in municipal wastewater treatment plants [69]. Since the current statistical data are not fully consistent with those required for the inventory preparation, improved documentation of waste management practices at the regional level in China would contribute to improving the accuracy of the estimations of CH_4 generation.

Although CH_4 emission data are not as prevalent as CO_2 data, several recent estimates of China's CH_4 emissions are available in the literature. Table 10 presents the inventory results regarding China's CH_4 emissions in some special years from the following sources: the SNCCCC (for China 2005), the EPA (for China 2005) and the EDGAR (for China 2005 and 2007). There are significant differences in the emission data between EDGAR [70] and China's national inventory 2005 in SNCCCC [20]. Prominently, the results in EDGAR [70] are much higher than those in other studies, and the discrepancies are concentrated on the emissions from coal mining, rice cultivation, oil and gas system leakage, and wastewater management. EPA's estimates are not much different from those of SNCCCC [20], though there are also many differences concerning concrete emission sources. The results in this study are closer to those in the latest China's National GHG Inventory 2005 [20] and fairly represent the overall CH_4 emissions in China. It deserves attention that the calculated emissions from livestock in this study are much lower than those in China's national inventory 2005, mainly due to the decreased census population of livestock during 2005–2007. For example, the non-dairy cattle decreased by 21.4% relative to 2005 [83].

Therefore, though uncertainty in the estimates of China's CH_4 emissions by reference to a variety of literatures is significant, especially in examining several single sources, the scale of the total CH_4 emission in China is unlikely to be affected significantly even by considering such uncertainties in both methods and data. It is conservatively estimated that China's CH_4 emissions amount to about 40 Tg.

Table 10
Some existing reports for the CH_4 emission inventory of China (Gg).

Emission source	China 2005 [20]	China 2005 [68]	China 2005 [70]	China 2008 [70]
Enteric fermentation	14,379	10,355	9824	10,467
Manure management	2864	912	1551	1638
Rice cultivation	7926	5754	13,215	14,410
Other agriculture sources	No data	47	15	16
Biomass combustion	2163	2394	3493	3461
Coal mining	12,922	12,244	23,115	25,780
Oil and natural gas system leakage	218	178	2069	2490
Fossil fuel combustion	126	1651	182	202
MSW landfill	2204	2189	3203	3634
Wastewater management	1620	6134.1	6369	6480
Total	44,419	41,856	63,033	68,578

5. Concluding remarks

As a potent greenhouse gas more than CO_2, methane remains in the atmosphere for a much shorter period, and consequently, stabilizing CH_4 emissions can have a dramatic impact on decreasing the buildup of greenhouse gases in the atmosphere [17,117]. Also, methane recovery and utilization will contribute to alternative renewable energy development, emission reduction of air pollutants, and local economic benefit [118–120]. Better knowledge of the current methane budget helps to reduce uncertainties in the future projections of climate change and design effective mitigation strategies and policies [68,119,121]. Our estimates of China's CH_4 emissions represent a reasonable and detailed approximation with the data and resources available, which can reflect the importance of CH_4 emissions for regional, national and global GHG emission inventories.

China's CH_4 emissions have an essential and unique impact on the GHG emission inventory. The total CH_4 emission in China 2007, estimated as 38.6 Tg, is equivalent to two thirds of China's CO_2 emission by the global thermodynamic potential factor of 115.51; and even by the commonly referred lower IPCC global warming potential factor of 25 it is equivalent to one seventh of China's CO_2 emission and in magnitude greater than the nationwide CO_2 emissions in some developed countries, such as England, Canada, and Germany in 2007. Though the gross CH_4 emission in China was 1.5 times that in USA in 2007, the emission per-capita in China is only about one thirds of that in USA. Distinctive differences are identified for the emission structures between China and USA. The

current pattern of CH_4 emissions implies the tremendous reduction potential in China's energy fields. Since coal mining is the largest single emission source, reasonable exploitation of coal resources and effective utilization of coalbed methane have good penetration potential in China [98,122]. Energy policies for emission reduction from oil and natural gas system leakage and biofuel combustion can also make significant strides toward CH_4 emission mitigation. Meanwhile, methane recovery rooted in MSW, organic wastewater, and sewage treatment plants deserves to be implemented more rigorously. Fortunately, some of the policies and technological options for the purpose of CH_4 emission mitigation are emerging in China at different stages of development, especially in some CDM (Clean Development Mechanism) projects.

The geographical distribution of the CH_4 emissions in China has significant regional differences, and there exists a large gap in the potential reduction capability between the eastern and the central and western regions. Unlike CO_2 emissions mainly from the energy-intensive eastern regions [14], the focused areas of CO_2 emission reduction, the least CH_4 emissions occur in the eastern coastal regions with lower per-capita emissions and emission intensities. The Western and Central areas contribute 70.8% of the nationwide total emission. Specifically, Shanxi is the largest CH_4 emitter with an emission amount of 4594 Gg, and the four regions of Henan, Sichuan, Guizhou, and Hunan also generate very large amounts of CH_4, owing to massive emissions from coal mining and agricultural activities. The five regions of Xizang (Tibet), Shanxi, Qinghai, Ningxia, and Guizhou are identified with the largest emissions per-capita and emission intensities . By integrating CH_4 emission quantity and structure with emission per-capita and emission intensity at the regional level, the mitigation potential in some western and central regions is huge. Shanxi, Henan, Sichuan and Guizhou in the western and central areas should be the foremost policy target for CH_4 emission reduction and control.

Along with the consumption structure upgrade and urbanization processes, China's CH_4 emissions are likely to increase rather than diminish in the future. Increased meat consumption, centralized feeding modes, and consumer preferences change on agricultural product demand continue to contribute to CH_4 emission increases in the agriculture sector. Fugitive CH_4 emissions are expected to grow rapidly driven by sustained coal mining activities and robust energy demand. Increases in urban waste generation and population also drive the waste emissions upward though increases in waste-related regulations and gas recovery and use may partly temper this increase. EPA [68] provided an emission projection that China's CH_4 emissions in 2020 and 2030 will reach 1188.8 and 1302.5 Mt CO_2-eq by the lower GWP factor of 25, respectively. All these reflect the unprecedented emergency of CH_4 emission control in China and address the role of CH_4 emissions in climate change mitigation. To establishing updated emission data and corresponding mitigation potential, we also suggest enhancing data monitoring and statistical analysis at the national and sub-national levels in China's consistent efforts to reduce non-GHG emissions.

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